Tevatron Collider Working Group Report*

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Abstract

The Tevatron Collider Working Group studied the possible physics interests at a much higher intensity Tevatron Collider operating after BTeV and after the LHC experiments have already collected a large dataset. The group studied the physics opportunities afforded by the unique features of the Tevatron including reviews of b- and c-quark flavor physics, high p_T physics, QCD physics and possible fixed-target programs at 1 TeV. With sufficient increase in luminosity the Tevatron could offer some interesting physics opportunities, however the path for increased luminosity would most likely involve a significant number of potentially expensive and non-trivial upgrades to the accelerator complex, and even then only a modest increase would be gained. Some of the other interesting physics that could be done at the Tevatron does not rely on increased luminosity. It is concluded that it looks unlikely the physics opportunities at the Tevatron in about 2015 would add to a strong physics case for the proton driver.

*This Working Group was part of the Fermilab Proton Driver Workshop, held at Fermi National Accelerator Laboratory, 6–9 October 2004 [1].

1 Introduction

This working group was devoted to physics studies relating to the Tevatron Collider in the era of a 2 MW proton driver. This is one of the working groups created in order to try to do as thorough a job as possible in exploring and documenting the breadth of the physics case for a high intensity proton driver.

The Tevatron Working Group studied the possible physics interests at a much higher intensity Tevatron Collider operating after BTeV and after the LHC experiments have already collected a large dataset. The charge to the group was to review the various areas of physics that a higher intensity/luminosity Tevatron could contribute in 2015, and comment on the relative interest in each area. The date of 2015 was chosen to provide a definite date for consideration. An integrated luminosity increase of a factor of 3–10 more than Run II was also given to provide a more definite basis for comparisons. For discussions of fixed-target physics programs, an increase of a factor of 10 in intensity rate compared to earlier Tevatron fixed-target runs was considered. Also an increase in proton beam energies from 800 GeV to 1 TeV was also considered. The required changes to the accelerator complex to achieve these increases in luminosity and fixed-target intensities were also reviewed.

The group studied the physics opportunities afforded by the unique features of the Tevatron. This included reviews of b- and c-quark flavor physics, high p_T physics, QCD physics and possible fixed-target programs at 1 TeV. The unique features of the Tevatron compared to the LHC include differences in production and backgrounds for a collider using antiprotons and operating at lower energies. The working group program for the workshop consisted of a small number of excellent well focused talks on these topics [2] and there were discussions afterwards amongst the small number of people in attendance for this working group. The talks that we had are given below:

- **Ulrich Nierste**, *Fermilab*, "Charm and Bottom Physics in 2015 and Beyond."
- **Tim Tait**, *Argonne*, "High p_T in 2015."
- **Bogdan Dobrescu**, *Fermilab*, "New Physics Searches at the Tevatron in 2015."

- **Mike Albrow**, *Fermilab*, “The Proton Driver and the Tevatron Collider.”
- **Ted Barnes**, *ORNL and Univ. of Tennessee*, “WA102 and Meson Spectroscopy.”
- **Paul Derwent**, *Fermilab*, “Antiproton Source and the Proton Driver.”
- **Vladimir Shiltsev**, *Fermilab*, “Can the PD/8 GeV Linac Help the Tevatron?”

Although there is a lot more work that could be done to investigate the ideas outlined in this report in more detail, we feel that we have reviewed the topics adequately to provide some relevant conclusions. These are given at the end of the report after reviewing each of the above topics in more detail.

2 Charm and Bottom Physics

The case for quark flavor physics is a good one even after several years of data-taking at the LHC and even if an ILC is running. A lot is being done on charged B and B_d^0 decays by BaBar and BELLE and this will continue. These studies will be made more precise and expanded to new and more rare decay modes as well as to studies of other b particles, *e.g.* B_s^0, B_c and Λ_b, by BTeV and LHCb. There is and still will be interest in 2015 on flavor physics because rare or SM forbidden decays can probe scales up to 100 TeV, well beyond possible direct observations at the LHC or an eventual ILC. Besides looking for new physics in for example rare decays or in comprehensive studies of CP violation in b-decays, if physics beyond the Standard Model is found elsewhere like ATLAS or CMS, results on the parameters from flavor physics can help distinguish between the different models of New Physics that would otherwise be extremely difficult. For example, it is very difficult to study precisely FCNC decays of squarks. By 2015 the study of b-physics would no longer be motivated by “unitarity triangle trigonometry”. We would want to study theoretically clean observables and very rare processes. An example of the latter, given by Ulrich Nierste, is the “near zero” SM prediction of the CP asymmetry in the flavor-specific decay $B_s \to f$, *i.e.* $B_s \not\to \bar{f}$ and $\bar{B}_s \not\to f$. For example $B_s \to X\ell^+\nu_\ell$ or $B_s \to D_s^-\pi^+$. In the SM the asymmetry

$$a_{f_s} = 2 \times 10^{-5} \propto |V_{us}|^2 \frac{m_c^2}{m_b^2}.$$

The suppression factor $|V_{us}|^2(m_c^2/m_b^2)$ is absent in new physics scenarios with new non-CKM contributions to $B_s - \bar{B}_s$ mixing. An enhancement by a factor of about 200 in a_{f_s} is possible.

The interest will not be limited to b-quark physics. For example once new physics like SUSY is found there will be increased interest in D^0-$\bar{D}^0$ mixing. SM short-distance contributions to D^0-$\bar{D}^0$ mixing is tiny and though the long-distance effects are larger and difficult to calculate, new physics can contribute through loop diagrams and will be calculable once their mass scale is determined. This can lead to precise tests of the nature of the new physics observed. Even if the new physics contributions to D^0-$\bar{D}^0$ mixing are smaller than the long-distance SM effects, one can still look at mixing-induced CP asymmetry in charm, *e.g.* $D^0 \to KK$, $K\pi$, or $\pi\pi$.

$$A_{CP} \sim 2(x\cos\delta + y\sin\delta)\sin\phi\Gamma_D t,$$

where $x = \Delta m_D/\Gamma_D$, $y = \Delta\Gamma_D/2\Gamma_D$, δ is the strong rescattering phase, and ϕ is the mixing phase which is tiny in the SM ($\phi < 10^{-3}$). New physics scenarios give $-1 \le \sin\phi \le 1$ and can thus act as a more sensitive probe of new physics.

We can conclude by basically quoting Ulrich Nierste's summary slide. In 2015 precision quark flavor physics will either continue, via indirect searches, to explore new physics beyond the energy range for direct observations or if new particles are found at the LHC, the flavor structure of the new particles will be probed. If the world is supersymmetric, flavor physics will teach us something about the SUSY breaking mechanism.

Some of the important charm and bottom physics would already have been done by 2015 by BTeV and LHCb. These experiments will each have collected in the neighborhood of 5–8 fb^{-1} by 2015, thus we expect them to have already produced many important results. However the studies of the very rare decay modes which might be especially clean would be able to be improved upon. It is unclear what the upgrade plans for LHCb would be since they will already be running at a much lower luminosity than for CMS and ATLAS to keep the number of interactions per crossing at one or less. Presumably major upgrades to the detector and trigger/DAQ would be required. The LHC crossing time is already 25 ns so reducing this to reduce the number of interactions per crossing would be challenging. The situation for BTeV running at the Tevatron is more clear since they can gain a factor of 2 in statistics by adding another spectrometer arm. However they too would probably be limited by the number of interactions per crossing, and thus would not desire a larger peak instantaneous luminosity if the crossing time stayed at 396 ns. If the crossing time could be reduce say to 132 ns then BTeV should be able to take 3 times their nominal peak luminosity. With a second arm as well as reducing the crossing time it is theoretically possible for BTeV to improve its data-taking rate by a factor of six. However there are important accelerator issues related to this which will be touched on in the section on the Tevatron Collider.

3 High p_T Physics

The area of high p_T physics is not an obvious place to look for physics opportunities at the Tevatron in 2015. By that time there would have been several years of data-taking at the LHC, with an integrated data-set of about 300 fb^{-1} for CMS and ATLAS. There is quite a lot of information on what physics would have been done with such a data-set, some good reviews were given at HCP2004 [3], and Tim Tait reviewed a sample of these at the working group session, including Top physics, Higgs, Supersymmetry, Extra Dimensions, and W' and Z' bosons.

By 2015 the experiments at the LHC would have made great progress in exploring the high energy frontier:

- Anomalous Top physics should be discovered or bounded to $\sim 10^{-3}$;
- if a SM-like or MSSM-like Higgs existed we would probably know, though there would still be much to discover, for example the couplings would either be measured to the 10% level or not measured at all, and there would still be uncertainty as to whether what was seen was really the Higgs or not;
- if nature is Supersymmetric some sparticles would be seen, but much more would be unknown;
- some effects of Extra Dimensions if they were due to phenomena at the 1 TeV scale should be seen but distinguishing the effects of some types of ED's (e.g. Universal ED) from SUSY effects might prove challenging;
- it is possible that evidence for W' and Z' bosons could be found but their interactions would not be well known.

Some of these important questions can be addressed by quark flavor physics as mentioned in the previous section, and of course by an ILC which may become a reality by 2015. However it was interesting to find out at this workshop that there may still be niches of opportunities at the Tevatron Collider given sufficient luminosity.

The opportunities for high p_T physics at the Tevatron after the LHC has started producing physics have not been well studied. This is natural since it is very hard to compete with the LHC and even harder to compete when the ILC enters the picture. Previous high luminosity Tevatron physics studies concentrated on physics that would be better done at the LHC, so although there is a lot of material for these earlier studies [4] much of it is not relevant for 2015. However some examples of physics beyond the SM where the Tevatron would still be useful after the LHC were described by Bogdan Dobrescu. These have to do with the smaller backgrounds for some specific decays at the Tevatron and the fact that there are more antiprotons per collision for a $p\bar{p}$ collision compared to pp collisions. The physics examples given still require large integrated luminosities 30–100 fb^{-1}, and he warned that although one can always find some physics scenario where the Tevatron is still useful, one cannot say how likely these scenarios are.

A few examples of physics scenarios include a light stop in the MSSM where the dominant decay is $\tilde{t} \to c\chi_1^0$ for $m_{\tilde{t}} < m_t + m_\chi$. The current search mode used in Run II at the Tevatron, $\tilde{t}\tilde{t}^* \to c\bar{c}\ \not{E}_T$, would be very challenging at the LHC because of large backgrounds. Another example is a light Higgs, 115 GeV $< M_h <$ 130 GeV, where the $hb\bar{b}$ coupling could be measured with the Higgs produced associated with a W, $q\bar{q} \to W^* \to hW$, and with $h \to b\bar{b}$. There is a huge $b\bar{b}$ background for this at the LHC. A third example is the leptophobic Z' which does not couple to leptons so that LEP and the ILC will not provide useful bounds while the LHC would have large dijet backgrounds. Thus a high luminosity Tevatron would probably represent the best chance of discovering a leptophobic Z'.

Although it would be very hard in 2015 to compete with the LHC in high p_T physics and even harder to compete with the addition of the ILC, there are possible niches of physics opportunities for a high luminosity Tevatron Collider if one could collect an integrated luminosity of about 30–100 fb^{-1}. However one cannot tell how probable these physics scenarios are but it will be easier to guess once ATLAS and CMS start producing physics results.

4 QCD Physics

There is currently already a very active program of QCD physics at both CDF and D0 and this will continue until about 2009 when the LHC will presumably take over in many areas of QCD physics. One can try to study the strong interaction and test QCD at all distance scales, rather than just perturbative QCD in high p_T processes. These include studies in the forward region (lower p_T or larger distance scales), the diffractive sector and spectroscopy. The search and study of different quark and gluon states, both exotic or otherwise (e.g. glueballs and hybrids), can benefit from detectors in the forward and very forward regions [5, 6].

The current program of QCD physics at the Tevatron could be expanded especially into the very forward region by the addition of precision silicon detectors in roman pots and upgrades to very forward cone spectrometers. This is a relatively unexplored territory. There are currently other subgroups convened to look at this opportunity, *e.g.* at the TeV4LHC Workshop [7], but the likely priority is low for any significant modifications of the CDF or D0 detectors to enable the forward/diffractive physics capabilities before 2009. There have been studies of the possibilities for such modifications after 2009, *e.g.* at a previous workshop associated with the GTeV initiative [5]. Some suggestions of additions to the BTeV detector for diffractive physics were also raised. Although some of the physics channels are rare, the QCD studies one would want to do at the Tevatron require clean events and therefore not more than one interaction per crossing. This means that it is unlikely that a high luminosity Tevatron Collider would be needed for these QCD studies.

5 Fixed-Target Physics

Although the Tevatron fixed-target program ended in 1999 and there are currently no plans for its return, we decided nevertheless to include discussions of the opportunities if there were a high intensity Tevatron fixed-target program in 2015 with up to ten times the intensity rate that was available previously.

Generally there is not much interest in a high energy neutrino beam for oscillation studies since the baseline for a ~ 0.8–1 TeV neutrino beam would be too long for the parameters of interest. Also the intensity rate would normally be lower than for beams from an earlier stage of the accelerator train. Although the τ neutrino was directly observed for the first time at the Tevatron in the DONUT experiment and the study of this neutrino could by itself conceivably make a strong physics case for a proposal, a detailed study of the ν_τ would not be possible in 2015 at the Tevatron even with a proton driver and other necessary machine modifications. At least a factor of 200 more data than that collected by DONUT would be needed to make even this low statistics study worthwhile. Ideally one needs much more intensity but preferably much higher energy beams to produce more copious τ neutrinos.

There was some interest previously in measuring $\sin^2\theta_W$ using a high energy neutrino beam to try to confirm the value measured by NuTeV [8]. However the proponents of that idea are now more interested in doing this measurement at a reactor experiment [9], where important oscillation studies can also be done at the same time. This latter experiment and the former proposal are supposed to be able to measure $\sin^2\theta_W$ to about 1%, which is almost as precise as the NuTeV result. A more definitive measurement might be possible for a ~ 1 TeV neutrino beam of much higher luminosity than in previous fixed-target runs but there was no discussion of this at the working group sessions.

Another topic of discussion was the study of hyperons, such as their rare and radiative decays, and the search for CP violation in hyperon decays. These studies do not benefit from higher luminosities but they would benefit from higher energies. The addition of a proton driver would not help significantly in getting higher energy Tevatron beams.

6 Machine Physics

One can see from the preceding sections that there should still be interesting physics opportunities at the Tevatron in 2015 even though the LHC experiments would have started producing results and after BTeV and LHCb have run. This is true if one can get substantially more integrated luminosity than in Run II, about 30–100 fb^{-1}. We had two excellent talks that addressed the feasibility of this by Paul Derwent on the Antiproton Source and Vladimir Shiltsev on the Tevatron Collider.

In the 1996 TeV33 study [4,10,11] various upgrades were considered that were thought to be able to increase the Tevatron luminosity to 10^{33} cm^{-2}s^{-1}. The most likely path was thought to be increasing the antiproton stacking rate and the number of bunches in the Tevatron. Many of the proposed upgrades were considered, studied and implemented or soon to be implemented for Run IIb. Some upgrades are not going as envisioned in 1996, for example the recycler will not be used for recovering antiprotons from the Tevatron at the end of a store, but only as a means of stashing more antiprotons to build larger antiproton stacks. However other upgrades have gone better than expected, for example the rate of protons on the antiproton production target has been increased substantially by the Slip Stacking that was already implemented for Run IIa.

The antiproton stacking rate is not limited by the rate of protons on target but by the cooling in the Debuncher and Accumulator. With the addition of a proton driver it would take a substantial number of significant upgrades to be able to increase the antiproton stacking rate beyond that planned for Run IIb. These steps were outlined by Paul Derwent and include for example doubling the Debuncher cooling performance which would probably need a new ring to provide another cooling orbit. Even including all the upgrades outlined, none of which are easy, one could only expect an increase of a factor of about two in the antiproton stacking rate and in the number of antiprotons available for the Tevatron.

The method of increasing the Tevatron luminosity by increasing the number of bunches has already been abandoned for Run IIb. Although this was thought to be the most likely path to an increase in the instantaneous luminosity by the TeV33 study group, it was found that the effects of beam-beam interactions and intra-beam-scattering have been much larger than expected and an increase in the number of bunches is not expected to produce a gain in the integrated luminosity. In particular increasing the number of bunches by three (and thus reducing the crossing time to 132 ns) would need a significant crossing angle and loss of luminosity. Such a reduction of crossing time would be needed if for example one wanted to run BTeV with a much higher peak luminosity than their design of 2×10^{32} cm^{-2}s^{-1}.

The integrated luminosity is the primary quantity of interest and is governed by the peak luminosity and the luminosity lifetime. Vladimir Shiltsev gave an overview of these two quantities including creating a simple model for estimating the luminosity lifetime since many parameters can affect this. The conclusion is that if one can get a factor of two more antiprotons, and the effects of beam-beam interactions can be reduced by a beam-beam compensation upgrade, then an increase of a factor of about 2.4–3 might be possible in the integrated luminosity/year.

As regards a possible Tevatron fixed-target program, an extraction region would have to be recreated. Without antiprotons in the Tevatron and with some other modifications it would be possible for the Tevatron to deliver 3–6$\times 10^{13}$ protons in 100 bunches at 980 GeV if the Main Injector could inject these protons quickly enough. With coalescing, the injection from the MI would take about 30 minutes to fill the Tevatron which is too slow. If coalescing is not done then the MI can deliver about 5.5×10^{13} protons which could be ramped to 980 GeV "safely" if one installs modified longitudinal and transverse instability dampers. Thus it looks possible to deliver a rate of protons that represents an increase of a factor of 2–3 over that for the 1996–1997 fixed-target program.

We conclude this section by noting that even with a significant number of expensive and/or non-trival upgrades one can at most expect a factor of 3 increase in the integrated luminosity. This might make a goal of 30 fb^{-1} possible in the 2015–2020 time frame but not 100 fb^{-1}. Also the expected increase in intensity of a possible fixed target beam from the addition of a proton driver is also not expected to be sufficient to arouse interest in starting up a new Tevatron fixed-target program.

7 Conclusions

With sufficient increase in luminosity the Tevatron could offer some interesting physics opportunities in about 2015 even though the LHC would have started producing physics results and after BTeV and LHCb would have run. However the path for increased luminosity would most likely involve a significant number of potentially expensive and non-trivial upgrades to the accelerator complex, and even then only a modest increase would be gained. Some of the other interesting physics that could be done at the Tevatron does not rely on increased luminosity. Thus it looks unlikely the physics opportunities at the Tevatron in about 2015 would add to a strong physics case for the proton driver.

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